Problems of Automatic Vectorization
of Artwork

Robert Thibadeau

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A number of attempts have been made to scan printed wiring artwork, or drawings of circuit layouts, for automatic entry into computer aided design systems. Several commercial machines are available which accomplish forms of artwork vectorization. The Inspection Laboratory, under the sponsorship of Visual Understanding Systems, Inc., has worked on the problem of vectorization. Most recently this work is based on a small, relatively inexpensive, vectorization system composed of an IBM/XT, custom electronics hardware, and 300 DPI scanner. This report will summarize our findings to date and indicate the capability of current "vectorization" technology.

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Abstract

A number of attempts have been made to scan printed wiring artwork, or drawings of circuit layouts, for automatic entry into computer aided design systems. Several commercial machines are available which accomplish forms of artwork vectorization. The Inspection Laboratory, under the sponsorship of Visual Understanding Systems, Inc., has worked on the problem of vectorization. Most recently this work is based on a small, relatively inexpensive, vectorization system composed of an IBM/XT, custom electronics hardware, and 300 DPI scanner. This report will summarize our findings to date and indicate the capability of current "vectorization" technology.

1. Introduction

A number of attempts have been made to scan printed wiring artwork, or drawings of circuit layouts, for automatic entry into computer aided design systems. This would permit the large body of hand-taped work and photoplot artwork to be readily integrated into modern CAD/CAE control systems. An added benefit would be that artwork could simply be drawn with a straight-edge on paper and then automatically scanned for photoplot. The scanning technique is generally referred to as *artwork vectorization* because a rasterized camera image must be transformed into a series of photoplotter point-to-point draws and single point flashes of different shapes or apertures.

Scanner

SCAD → Output Device

Input Device → CAD System
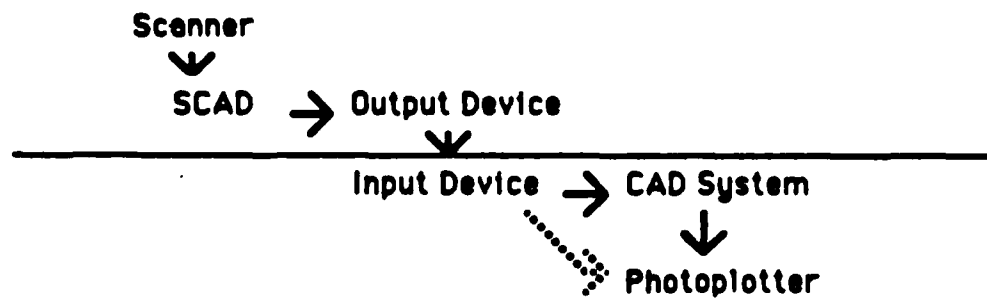
Photoplotter

Figure 1-1: Scan to CAD System takes the original document and produces information for a CAD system, or, perhaps, directly for the photoplotter.

Several commercial machines are available which accomplish forms of artwork vectorization. For example, Scitex has one machine which will scan and reproduce, but not reverse engineer for CAD. Visual Understanding Systems, Optrotech, and Scitex (in added software) claim to reverse engineer. But the fact is that research is continuing to find ways to increase the automatization and reduce the amount of post-vectorization editing. Research is also welcome on discovering man-machine efficiencies in editing itself.

The Inspection Laboratory, under the sponsorship of Visual Understanding Systems, Inc., has worked on the problem of vectorization. Most recently this work is based on the small, relatively inexpensive, vectorization system composed of an IBM/XT, custom electronics hardware, and 300 DPI scanner, shown in Figure 1-2. This report will summarize our findings to date and indicate the capability of current "vectorization" technology.
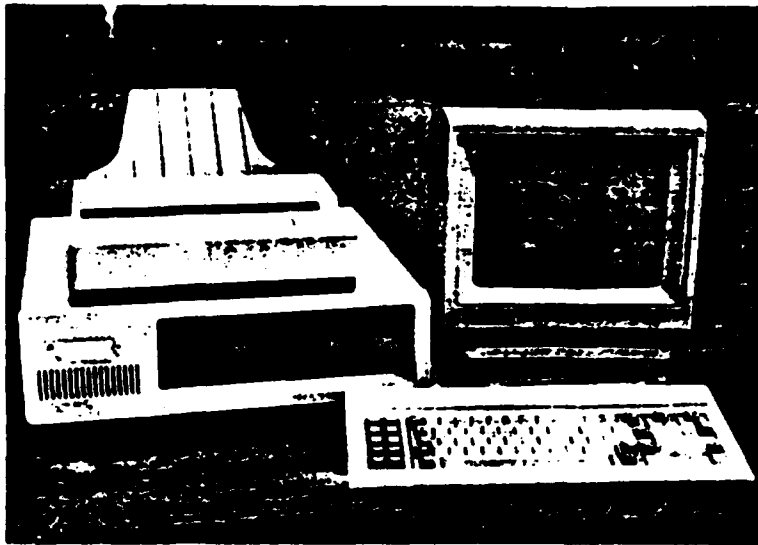
Figure 1-2: The VVS System from Visual Understanding Systems, Inc.

2. The *Model Driven* Model

The theory of operation which I propose for the "reverse engineering" process derives from early work in Artificial Intelligence called "expectation-based reasoning" (Sridharan and Schmidt, 1978; Thibadeau, 1986) and later in vision and robotics called "model-driven" (O'Gorman & Sanderson, 1984) and "composite model" processing (Crowley, 1984). Most fundamentally, "reverse engineering" is not seen as a process of piecing together information from the scanner, but of constructing a model of what the original drawing or artwork intended. As suggested by Figure 2-1, this model is a physical representation of a photoplotting.

The model may not exactly correspond to what the scanner "sees". In fact, there are many reasons, not the least of which is physical deterioration and imperfection, to avoid representing exactly what the physical artwork or drawing looks like. An illustration of some of the problems for hand-taped artwork is shown in Figure 2-2.

The model-driven image processing method breaks down the reverse engineering task as:
1. scanning,

2. the recovery of physical features of the scanned material,

3. the reconstruction of the physical layout from the features and the model constraints,

4. the manual editing process to finely adjust the reverse engineering to be as correct as necessary.

It is important to realize that (1), (2), and (3) can be automatic, or nearly automatic processes, and that the overall performance of the system can be judged by the amount of manual editing, (4), ultimately required to get the artwork or drawing into a format suitable for the photoplotter.

Figure 2-3 shows the typical construction of the automatic processes in greater detail than Figure 2-1.

Physical Model

Image Data

Procedures ⟶ Results

User Data
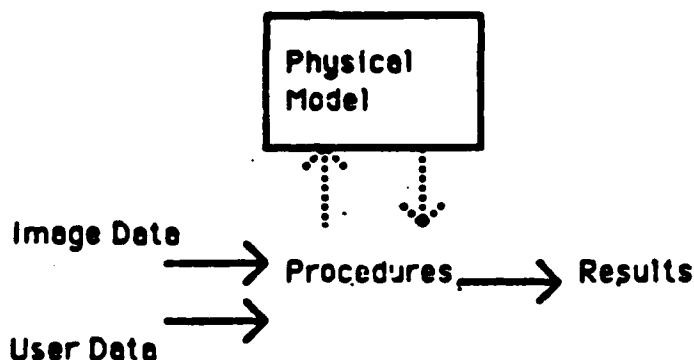
Figure 2-1: Scan to CAD constructs a physical model of the scanned input in order to convey information acceptable to CAD.

Complexity = Physical Record + Scanning Error + Intentions

344

340

Defect (line misses pad)
Position (not on Grid)
Quantization (scanner)
Hand Taped (hole)

Precise Instructions
to Photoplot
on Gerber 33
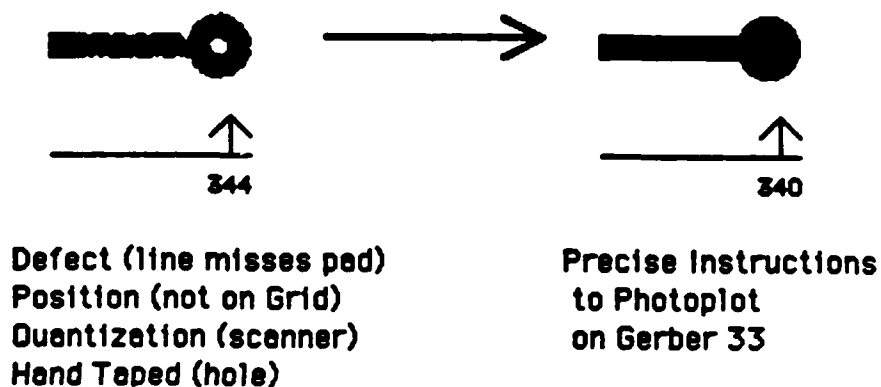
Figure 2-2: Problem of "vectorization" from a scanned image of hand-taped artwork

The User and Image Data are analysed and generated out of the Query and Feature Extraction systems under control of a Planning component. Planning applies Consistency and Completeness Constraints to determine whether the Physical Model is (a) a "good" photoplot, and (b) a "complete" representation of the information available from the scanned image and the User input.
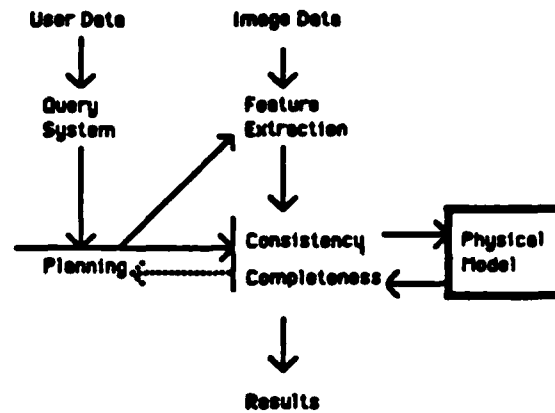
Figure 2-3: Automatic vectorization involves a planning component which
maintains consistency and seeks completeness in the physical model
of the original artwork.

3. Signal Cleanup Models

Model-driven methods can go from extremely simple to extremely complex. A simple method has essentially no active planning component. It could use a laser drum scanner which will also photoplot. In this method the Scanner provides a continuous signal which is digitized and then thresholded to produce the desired high contrast, binary, result. A model used to process the data may assume (a) that the data derives from a binary image, and (b) that the edge contours are smooth, or of a low spatial frequency. This simple model can be uniformly applied to the data to produce the result, which is a "cleaned up" re-written image.

The problem with this method is that it relies on the dimensional integrity and correctness of the original material. Defects, including dimensional deteriorations and photoplotting defects, are reproduced. A model can be much richer than simply a model that eliminates uniform noise. However, going hand-in-hand with the richer model is a richer base of physical information about the scanned images. In the simple drum scanner method, the information about the scanned images was edge information, nothing about lines and pads or draws and flashes. Nothing about apertures or alphanumeric characters. There was simply no such information abstracted for the model because the model did not require it.

4. CAD Models

In our experience, a rich model can always be found by reference to the activity of generating the CAD version, in this case, photoplotting. The Gerber photoplotting method, which continues to dominate this industry, involves the use of a wheel of apertures through which light is flashed to expose the film. Control of which aperture on the wheel is flashed and where in X and Y the flash is made then determines the photoplot. There is a mechanical difference between a precise step and flash (a "flash") and the

faster flashing while in motion (a "draw"). Reverse engineering a photoplot is, by this CAD/CAM model equivalent to identifying the apertures and how they were flashed and drawn over the surface of the film Since we require a model of this complexity to deal with hand drawn work and hand taped work, we will study this type of model here. It is more inclusive than the signal cleanup models.

A purely formal plan for the interpretation of the photoplot can be developed as a search process. The search would apply the universe of apertures and flashes and draws over the candidate artwork in order to deduce what aperatures and draws are possible in the physical data. Then a selection from the possible apertures and draws would be made by determining joint occurrences such as apertures available on single wheels. Finally, if there are any other ambiguous possibilities in conflict in the same physical space, a random selection of the draw and the aperture would occur. A model of the error would also apply to produce aperture and motion candidates from imperfect data, and to enable reconstruction of dimensional dependences. Such an approach would solve the reverse engineering problem by brute force. But, this formal search method is not extremely viable because of the computational complexity of brute-force matching the universe of apertures and motions. The number of pixel (*picture element*) operations on a modest piece of artwork would likely exceed the capacity of any practical computational architecture.

4.1. Aperture-Based CAD Model

This search space plan for interpretation can be modified to be more practical. This is done by allowing components of the derivation to be a construction process. So, for example, rather than searching through the space of all apertures and all motions, we might construct motions and search through apertures. This is particularly reasonable if we note that most photoplotter motions fall into two categories: (a) a simple draw or flash that stands largely by itself as a geometric object, and (b) a fill area in which the draw is a boustephedron path. By taking account of this typical, though by no means necessary, constraint on photoplotter motion we can reduce the computational load tremendously. Now practical "photoplotter speed" reverse engineering is possible with image processing equipment which matches pixels at rates of no more than a few scores of billions a second. We have earlier demonstrated such a device as a large format binary convolution processor (Thibadeau 1984; Berger, 1983, 1985; Thibadeau, 1985; Thibadeau and Gabrick, 1985).

In that device, a few match templates were used which represented apertures. The system could judge which apertures were not differentiable by a simple computation of scan resolution. These apertures were grouped. Each aperture group was applied as either a flash template or a draw template as seen in Figure 4-1. These would be treated differently in the matching. For example, a draw of a round aperture would be constrained to match a draw at some orientation, like vertical, 45 degree, or 90 degree. This would simplify the construction process. If a draw occurred along a curve, this would violate the simple model of *straight line draws*. Circular (or square) aperture templates are then used in a secondary process to follow the smooth curves.

It can be pointed out that the same large format binary convolver can be used to generate regression equations of first and second order at all points in an image (see Thibadeau, *forthcoming*). This more powerful process, which represents a constructive solution of both aperture and motion, is avoided because it is at least 42 times slower than the other primary template matching processes. Such a speed difference represents the difference between processing a photoplot in one hour and in forty hours.
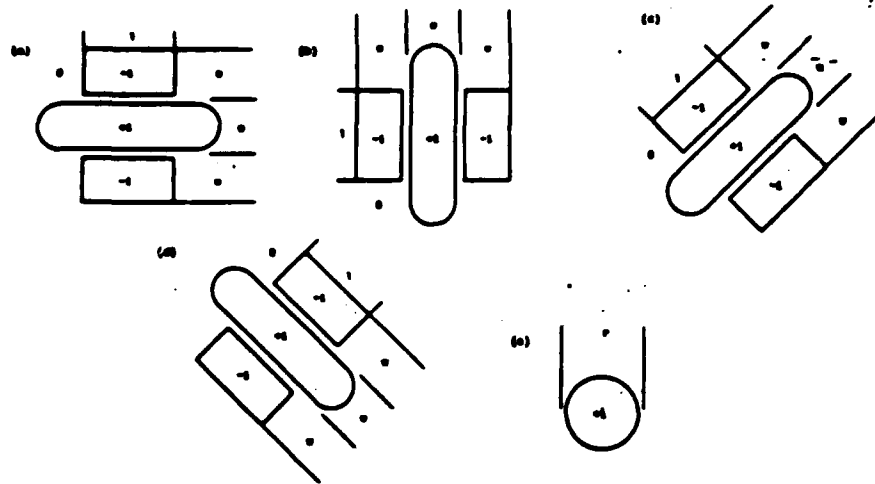
Figure 4-1: The use of an aperture model is illustrated with these templates which match lines at various orientations and flashes.

A variant on the aperture search model requires that all apertures used to photoplot the artwork oe flashed on a test coupon along with an indication of whether the aperture is used as a flash or draw. This reduces the search space of possible apertures to those known to be used on the photoplot. This technique therefore reduces the number of aperture groups and the ambiguity of the apertures in each group. In fact, given the widespread tendency to photoplot with just four or five apertures, the group size is often reduced to one and therefore there is little or no ambiguity in the reverse engineering.

It is rather surprising to construct artwork with a test coupon that anticipates the loss of the original CAD information, but the same techniques used to reverse engineer using the coupon now permit one to perform an artwork inspection. Here it is important that the apertures be displayed independently of the circuits so that the design rule inspection can be judged with a pre-defined set of apertures. Such coupons could also lead to design inspection, as opposed to the ad hoc inspection currently being used in the printed wiring industry. Artwork inspection is one of the desirable "spin-offs" of artwork vectorization.

4.1.1. Summary of Aperture Model Results

To summarize these observations: The search space model was reduced to a template or aperture model in order to be practical. The groupings of ambiguous templates were handled in one of two ways, either by algorithms which drive additional, often *ad hoc*, feature extraction or by relegating the disambiguation to the user in the manual clean-up. But the aperture model can successfully drive the interpretation of a photoplot. It is clear that the stronger the model, the easier the interpretation. Along with strong model constraints comes a reduction in the fields of use. The aperture models, because they are aperture based, perform relatively poorly for hand-taped and hand-drawn artwork where apertures are not used.

4.2. Vector-Based CAD Models

Another approach broadens the field of use by adopting a more general model. Where before the physical features were all directly aperture based, we can now approach the matter on draw-based, or vector-based features. One simple illustration of the difference in the two approaches should serve: In the case of a line with a neck-down, or narrowing, under the aperture model, the neck-down is interpreted as a separate draw from the lines to either side of it. However, in the vector-based model we first recognize the continuity of the circuit, viz., that there is a continuous line that can be drawn through the line and the neck down. Recognition that this continuous line changes its width is a function of a separate, line-associated, feature. A vector-based model is closer to the functional model of printed wiring as a conduit, than is the aperture-based model.

The vector-based approach replaces a series of template matching actions with a "vectorizing" process of a different sense. There are literally scores of such vectorizing methods which are in use today. They pair a line thinning algorithm with a line tracking algorithm. The purpose is to reduce the printed wiring traces to lines which are exactly one pixel wide. Then, line tracking algorithms follow the center lines of the traces by following the thinned lines. A property of this technique is that, unlike the template matching techniques, it can be implemented with inexpensive electronics hardware in order to achieve a practical implementation. The system seen in Figure 1-2 uses this method, and its electronics cost is on the order of one tenth the cost of the electronics used in the aperture method. The electronics hardware supports hundreds of millions, rather than scores of billions, of pixel operations a second.

Vectorizing is illustrated in Figure 4-2. The original image wiring is thinned down to lines which are a single pixel thick. These traces are then tracked and straight line segments (or other polynomials) are fitted to the traces. The data is therefore transformed from a raster, pixel based, image to a set of Cartesian-coordinate pairs, or vectors. Much of the remainder of the processing is done on these pairs. However, both the thinned image and the original image is retained for further checks. For example, the thinned image is useful in checking for intersections and the original is useful in checking for pads and line widths.

The vectorizing method, because it constructs apertures, places less burden on the user to manage the model within an application. We have found this important in broadening the field of use. For example, the same device can be used for reverse engineering of photoplotted artwork, for converting hand-taped artwork into CAD format, and even for converting simple line drawings into CAD formatted printed wiring layouts. A further advantage of the vectorizing system are that pad-to-pad interconnects (viz., net-lists) are readily available to simple algorithms. Where our laboratory demonstrated the use of the aperture models in printed wiring inspection, the vectorizing method also lends itself to inspection as has been demonstrated by Ejiri (1973) and Mandeville (1985).

In order to properly exploit the wider fields of use of the vectorizing methods it is necessary to flexibly control the planning methods of the model-based interpretation. From studies in Artificial Intelligence we know that attribute-value, or so-called "schema-based", systems provide the expressive power in simple to implement mechanisms. An illustration of some schemas for control of the planning component are shown in Figure 4-3.

An example of the raw, unedited, results of vectorization are shown in check-plot format in Figure 4-4.
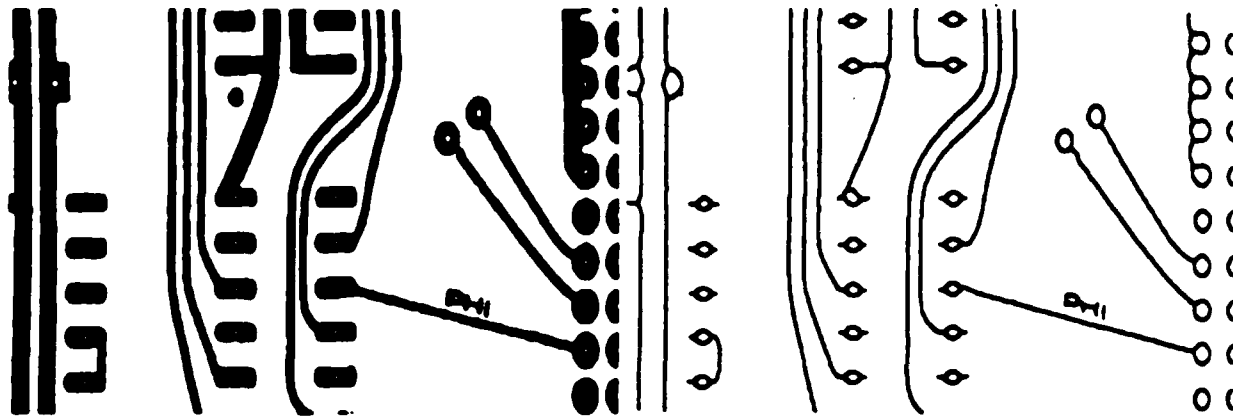
Figure 4-2: Vectorizing thins an original image into a one-pixel thick linework. This linework is represented as a set of straight line (or higher-order polynomial) segments.

PWB2:
    A PWB Layout with
        Style : Photoplotted
        Material : Film
        Fills : Fill20
        Traces : T14, T18
        Pads: P15, P132
        Text: F8
        Grid Size: 0.10

Fill20:
    A Fill Area with
        Aperture: Master(6)
        Class: SolidRaster

T18:
    A Trace with
        Aperture: Master(2)
        Angles: 0,90

Figure 4-3: Schemas for planning the interpretation of vectorizing. Each entry will signal different planning behavior which is guaranteed to be consistent or properly directed toward conflict resolution.

Figure 4-4: Unedited results from automatic vectorization, showing
the original and the check-plot result. The check-plot enables one
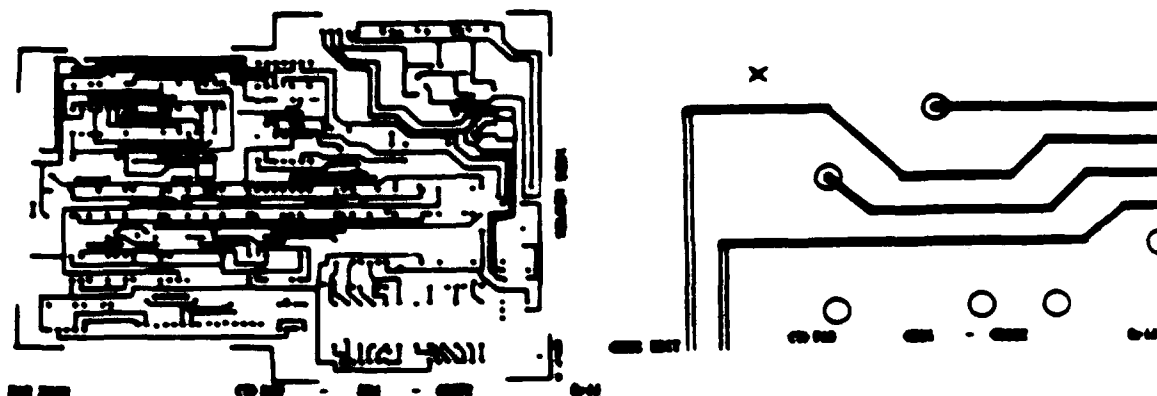to see the actual draws and flashes as they are used. Also note
that the line-widths are all the same, the display device corrupts
the diagonal lines and make them appear smaller.

5. Other Methods

The computer vision literature is rife with methods for analysing and representing line drawings, and, by extension, photoplots. We have focussed only on methods which are directly related in some functional sense to the photoplots. Just as important is whether a method can be implemented to operate at the speeds required. We have found that typically it is the speed criterion which leaves other solutions infeasible. However, another promising research avenue reconstructs the photoplot in terms of polygon approximations. This is neither aperture-preserving nor connection-preserving, and thus places a greater burden on active construction processes. So far, however, we have found that the more desirable methods are either aperture-preserving or connection-preserving.

6. Higher Order Entities

The vectorizing system should consider the recognition of entities other than simply the flashes and draws. For example, letters and numbers are formed of draws. Furthermore, it is desirable to recognize electronic component styles, such as the 14 Pin DIP package evident in Figure 4-4, connection fingers, and the like. If the system can identify these, then poor interpretations can be corrected and grid placements can be inferred with greater assurance. In general, it is more efficient to search for such entities in the feature space (e.g., pad positioning, draw organization) than in the raw image space. Our current preference is to have the machine search for higher order entities in the editor, after the draftsman has had the opportunity to set the final scale of the photoplot. Final scale and grid information drastically reduces the number of possibilities for interpreting higher order entities.

7. Editing

The major problem with automatic vectorization is, of course, that it is not completely automatic. Image interpretation processes have not been developed which can correctly account for anything that somebody places in a photoplot. This is particularly the case for hand-taped photoplots. Furthermore, with age and use, photoplots become scratched, get dusty, or incur other deterioration which will cause errors of vectorization which cannot in practice be avoided. It is therefore necessary to edit the results of automatic vectorization. A solution to the problem must incorporate a theory of editing. We have implemented several such theories of editing and have found that there are certain differences between editing automatically vectorized output and editing for CAD/CAE. That is to say, there exists a basic, incontravertible, theory which exists no matter what method of vectorizing is selected.

The points of the theory are (a) the editor must be, or have access to, a complete CAD/CAE system, and (b) the editor must have provision for Review. The need for a complete CAD/CAE system is stimulated by the fact that no method we have found is error-free in any aspect of CAD/CAE. The aperture method can still make errors in aperture selection (as was indicated for the case of visually ambiguous apertures), and the vector method can still make errors in connectivity (as was pointed out if scratches occur). A principle is that *there is no aspect of an interpretation which can be generically guaranteed correct by the automatic vectorizer.* It is important to realize this principle is not the same as alledging that a particular feature cannot be guaranteed. Often it is possible to guarantee particular features with such certainty that a person need never look at the machine's decision.
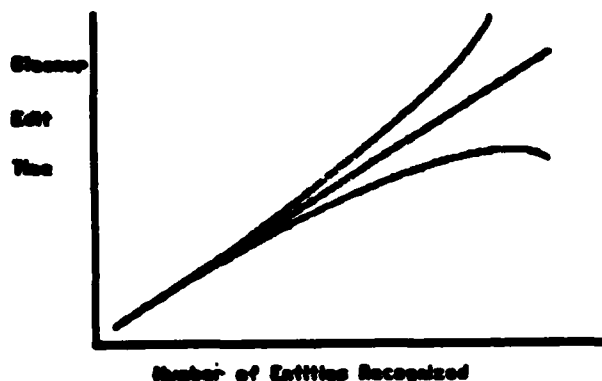

Figure 7-1: Possible relationships between the time to clean-up the vectorization results and the number of discrete types of entities which the system "automatically recognizes"

There is a fairly unpleasant consequence of this principle which is illustrated in Figure 7-1. There will be a tendency for a monotonically increasing relationship between the number of entity types which are recognized and the amount of clean-up editing required. Simpler, dumber, vectorization schemes could require less clean up because there is no attempt to recognize the underlying CAD/CAE entities.

However, counteracting this force in one direction is the fact that higher-order entities can constrain the interpretation of lower-order ones. If the system recognizes a 14 Pin DIP then 14 pads can be checked for placement and often at least as many lines. We do not yet have data available on the circumstances under which the curve in Figure 7-1 is monotonically decreasing (the preferred state) or monotically increasing.

The second point of a generic theory, that the editor must have provision for Review, is more subtle. Rarely do modern CAD/CAE systems include provision for a forced step-through of a layout. The reason is that *as the draftsman is contructing the photoplot he is forced through every facet of it.* Automatic vectorizing systems, although under control of planning mechanisms which try to assure consistency and completeness, are not foolproof. Since the draftsman does not have a feel for where the difficulties arose in assigning an interpretation for the photoplot, he must be led through the photoplot by the editing system. This assures that his attention will be focussed and that he can try to assure a complete review for consistency and completeness. An illustration of one such review mechanism is shown in Figure 7-2.
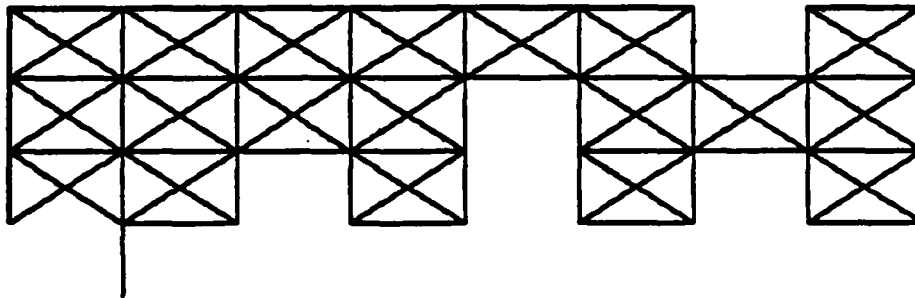
Crossed Areas are Done. Hit any Key to Continue

Figure 7-2: The VVS System, researched at our laboratory, incorporates
review tools such as a notepad which allows the draftsman with
one keystroke to indicate a subregion of the photoplot has been
checked or not.
The layout is scaled to the area shown above and the boxes
represent "screenfuls" at a given display scale. If there is an
"X" through the box, the draftsman has checked that area of the
layout as being OK. If not, the draftsman has a record of what
part of the layout he needs to consider further. Note that this editor
feature also allows the draftsman to be guaranteed to cover the entire
photoplot at any desired display scaling.

8. Concluding Remarks

The automatic vectorization of artwork is sometimes to considered to be unimportant because modern CAD/CAE systems are supposed to replace the need for paper or acetate transfers of information. The same logic applied to office automation which was supposed to eliminate the need for paper, but, in fact, the paper companies have thrived. Small engineering imperfections in CAD/CAE systems (like format incompatibility, database losses, difficulties in actually drafting and digitizing layouts, you can't carry your CAD system home) cause a real need for automatic vectorization which must be factored in to the design of modern CAD/CAE systems. This has been recognized by several Israeli companies and is now beginning to be recognized by U.S. researchers and vendors. In this paper, I have tried to outline the areas for needed applied research into this significant and interesting problem area.

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